Nonlinear interactions of regular waves with a truncated circular column

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ABSTRACT

In this present paper, wave elevations around single truncated circular column have been investigated by using a potential-flow solver (DIFFRACT) and a viscous-flow solver in OpenFOAM. Results from time-domain analyses have been compared with measured time series in experiments and results given by WAMIT. Spectral analyses have been carried out for time series to consider the contributions from wave components at different harmonics. RAOs and QTFs of surface elevations have been compared with the results obtained by Kristiansen et al. (2004).

INTRODUCTION

In recent years, increased attention has been focussed on the local amplification of free surface elevations due to large surface-piercing structural components, of particular importance for extreme wave impact on fixed or floating structures. Wave impact loads may have severe consequences if not properly considered in designs. Analytical or semi-analytical solutions can only be found for interactions between waves and structures with simple geometries (McCamy and Fuchs, 1954; Eatock Taylor and Hung, 1987). Most of the time, numerical tools and model tests are needed to provide acceptable predictions.

Numerical methods based on linear theory have been available for many years. Weakly nonlinear effects can be considered by introducing second-order theory. Several software packages can accomplish this in a potential flow framework, these include WAMIT, HYDROSTAR, DIFFRACT, ANSYS AQWA, etc. In this category, frequency-domain analysis is a quite efficient way to get linear amplifications factors (RAOs) and quadratic transfer functions (QTFs) of disturbed elevations. However, contributions from components above second order may also produce some novel phenomena. A good example is the 'ringing' which has been observed in model tests and prototype experiments on surface-piercing columns such as those in tension leg platforms (TLPs) and gravity-based structures (GBS). These may experience sudden bursts of highly amplified resonant vibrations during storms (Teng and Kato, 2002). Another question relevant to the accuracy of predictions in numerical simulations is the possible importance of viscous effects. It has been shown that potential flow solvers may generally over-predict local surface elevations in near-trapping problems. Viscous flow solvers may give quite accurate predictions when viscous damping is important, although solutions can require considerable computational resources. Much effort has been put into developing viscous flow solvers, and there are now also several free CFD software packages available. These include OpenFOAM (written in C++), REEF3D (written in C++), OpenFVM (written in C), dolfyn (written in FORTRAN), etc.

In the present paper, the focus is free surface elevations around a fixed truncated column subjected to regular incoming waves. The experiments have been described and analysed by Kristiansen et al. (2004). Both the potential flow solver DIFFRACT and a viscous flow solver in OpenFOAM have been used in current numerical analyses. A brief introduction of these two numerical packages will be given in section 2. In section 3, the experimental setup and selected waves conditions will be described. In the following section, time history of surface elevations at specified locations will be compared with measured data from experiments and numerical results given by Kristiansen et al. (2004). We concentrate on the free-surface motion close to the cylinder, presenting response amplitude operators (RAOs) and quadratic transfer functions (QTFs).

DESCRIPTION OF NUMERICAL MODELS

Potential flow solver DIFFRACT

The potential flow solver DIFFRACT has been developed in University of Oxford to solve three-dimensional wave diffraction and radiation problems up to second order (Eatock Taylor and Chau, 1992; Zang et al., 2006; Walker et al., 2008). The mathematical background of DIFFRACT is similar to that in WAMIT, a widely used commercial package.

However, there are also some different features in DIFFRACT. In this implementation of the boundary element method, the body surface, internal water plane and outer free surface for both linear and second order analysis are discretized into quadratic elements (Eatock Taylor and Chau, 1992). In the present version of the code, partial discontinuous elements have been adopted to provide efficient removal of the irregular frequencies, see Sun et al. (2008). Of particular relevance to this paper is the study by Zang et al. (2006), examining wave scattering from a stationary idealised ship-shaped body, where excellent agreement was obtained between experimental data from a wave channel at Imperial College and both linear and 2nd order predictions from DIFFRACT.

Viscous flow solver in OpenFOAM

OpenFOAM is a free open-source CFD package written in C++, which can solves compressible and incompressible Navier-Stokes equations on finite volume meshes. It uses a “Volume of Fluid” (VoF) approach to define the interface between different phases. A wide variety of turbulence models can also be selected for complex fluid-structure interaction problems. (OpenFOAM User Guide, 2013).

In recent years, OpenFOAM has become increasingly popular for applications in coastal and offshore engineering. Examples can be found in Morgan and Zang (2011), Chen et al. (2013). The recently reported remarkable comparisons with experiments for waves shoaling over submerged bars have indicated that the numerical model is able to accurately capture up to the 8th frequency harmonic in surface elevation (Morgan et al., 2010; Morgan and Zang, 2011)!

In the present paper, waves2Foam, a free toolbox is used to generate and absorb free surface water waves (Jacobsen, 2012). The main solver in this toolbox, waveFoam, is based on the original implementation of interFoam in OpenFOAM. InterFoam can track the interface between two incompressible fluids. Several algorithms are available to solve the important pressure-velocity coupling (OpenFOAM User Guide, 2013), such as PISO (Pressure Implicit Splitting Operators), SIMPLE (semi-implicit method for pressure-linked equations) and PIMPLE (merged PISO-SIMPLE). Here the latest PIMPLE algorithm has been adopted.

EXPERIMENTAL SETUP AND SELECTED WAVE CONDITIONS

Model tests of a truncated cylinder have been described in Kristiansen et al. (2004). They also carried out frequency-domain analyses using WAMIT. A brief review of the experimental setup will be given here. All information is presented as at full scale, after applying Froude scaling to the laboratory data. The radius of the cylinder is r=8.0 m and draft 24.0m. A top view of the experimental setup can be found in Fig. 1. Wave gauges were installed in a radial pattern around the cylinder, with distance from the cylinder wall of 0.05m, 1.5m, 4.7m and 8m. The 12 wave gauges were divided into 3 rows according to the relative directions to incoming wave (at 0, 45 and 90 deg respectively), these are shown as c1-4, b1-4 and a1-4 from the nearest to furthest to the cylinder in each row.

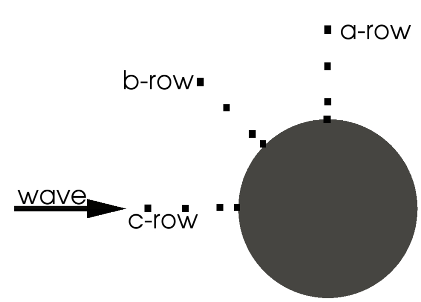


Fig. 1 Top view of experimental setup

Incoming waves at T=7s and T=15s have been selected in current analyses. For each wave period, waves with 3 steepness (H/L=1/30, 1/16 and 1/10) are chosen. Details of incident waves can be found in Table 1.

Table 1 Selected wave conditions

	T=7s (water depth: d=110m, wave length: L=76.44m, wave number:$k_0=0.082m^{-1}$, k_0d= 9.02)		T=15s (water depth: d=489 m, wave length: L=351.00m, wave number:$k_0=0.0179m^{-1}$, k_0d= 8.75)	
	wave height: H	wave amplitude: A	wave height: H	wave amplitude: A
H/L=1/30 $k_0A=0.1$	2.5480m	1.2740m	11.7000m	5.8500m
H/L=1/16 $k_0A=0.2$	4.7775m	2.3888m	21.9375m	10.9688m
H/L=1/10 $k_0A=0.3$	7.6440m	3.8220m	35.1000m	17.5500m

COMPARISONS WITH EXPERIMENTAL DATA AND WAMIT

Comparisons of time series

In this section, time histories at 3 locations (c2, b2 and a2) for steepest wave (H/L=1/10) at T=15s has been plotted with results given by Kristiansen et al. (2004) in Fig.2. It seems that time series obtained by using OpenFOAM give much better agreements with experiment than WAMIT ($1^{st}+2^{nd}$ order) at locations “c2” (upstream of the cylinder) and “b2” (out at 45 deg). However, such good agreement is not obtained for location “a2” (at the cylinder shoulder).

Of some significance is the appearance in both the experiments and the OpenFOAM results on the upstream side of the cylinder of a small transient pulse in the main trough of the signal. This may be related to the secondary load cycle in steep waves identified by Grue and Huseby (2002), see also the local free-surface displacements observed by Chaplin et al. (1997).

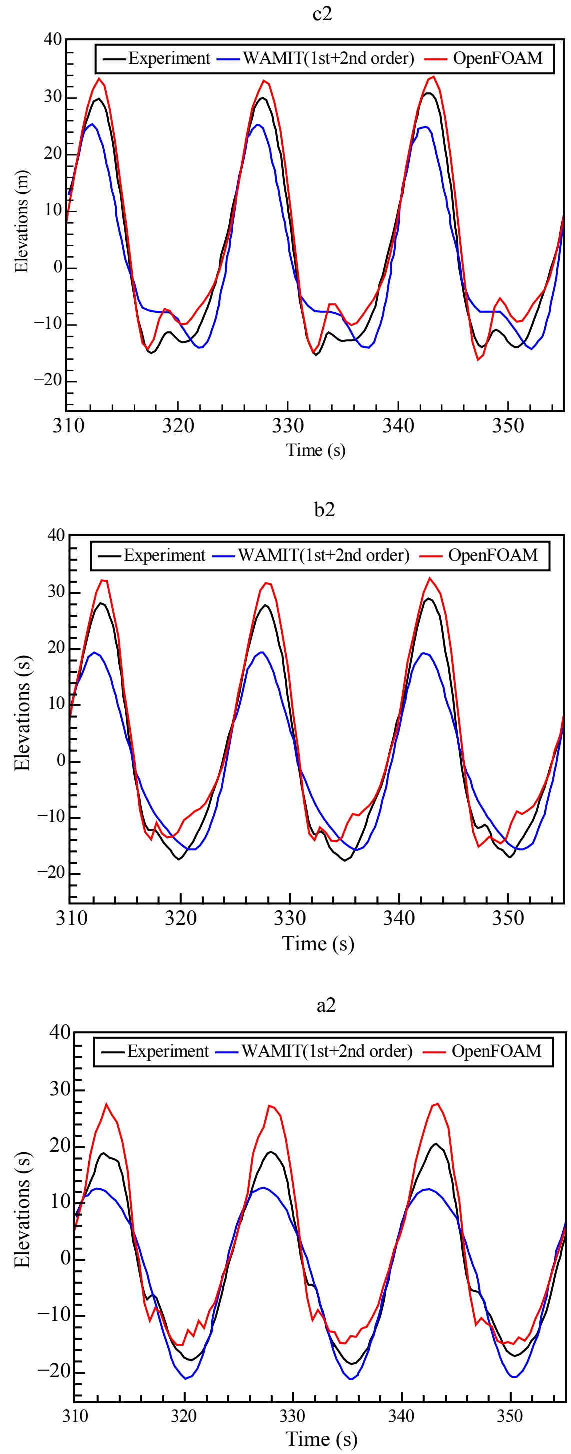
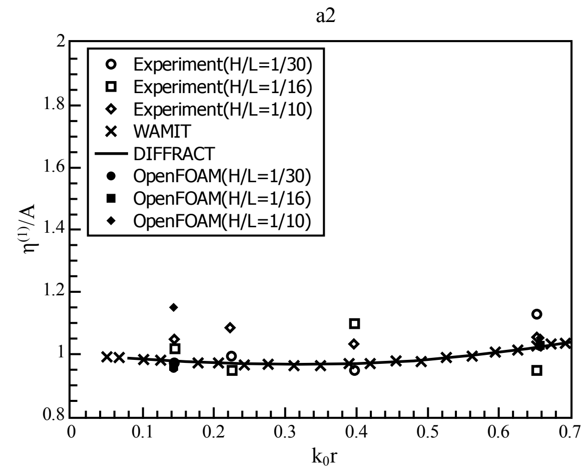
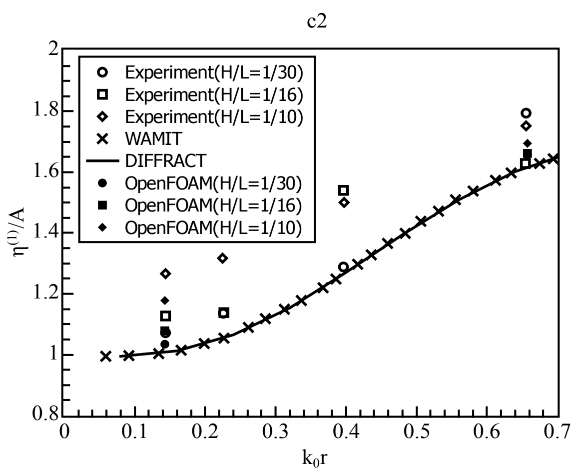


Fig.2 Time series at different locations for wave with H/L=1/10 at T=15s

Comparisons of RAOs and QTFs

It is straightforward to obtain RAOs and QTFs for frequency-domain analysis using the potential flow solver DIFFRACT. Contributions from different harmonic components at specified locations can also be obtained by spectral analyses from time series. RAOs and QTFs obtained in current analyses have been compared with published results (Kristiansen et al., 2004) as shown in Fig. 3, 4 and 5. As would be expected from two well-validated codes, good agreement is found for results from WAMIT and DIFFRACT, though for 2nd order calculations both codes require careful convergence tests (Birknes, 2001).





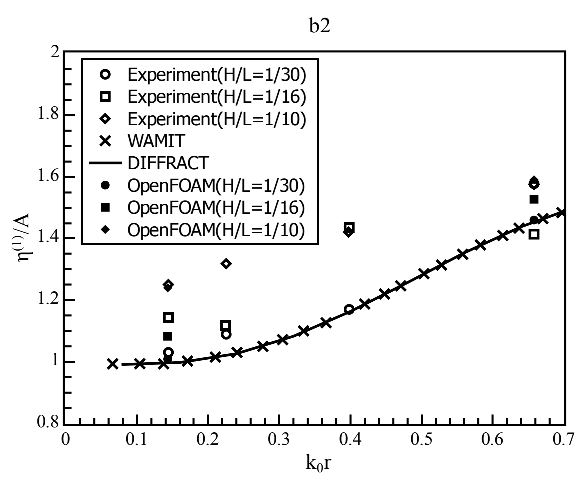
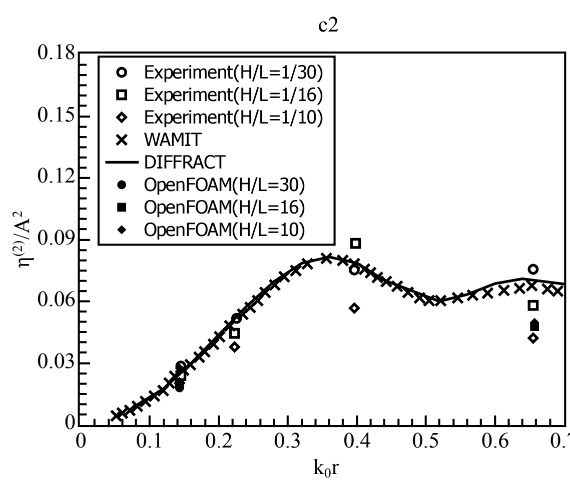


Fig.3 RAOs at different locations (1st harmonic component)

The 1st order results from potential flow theory (WAMIT and DIFFRACT) have been compared with the experimental 1st harmonic in Fig.3. Clearly, the linear simulations give low predictions. These discrepancies possibly come from the limitations of linear theory which can only consider the contribution of the first-order term. However, third-order terms may produce contributions to the 1st harmonic frequency in experiments in steep waves, with possibly limitations on this process from local wave breaking for the steepest waves. Generally, the viscous flow solver in OpenFOAM gives more accurate estimations for waves at T=15s and 7s.



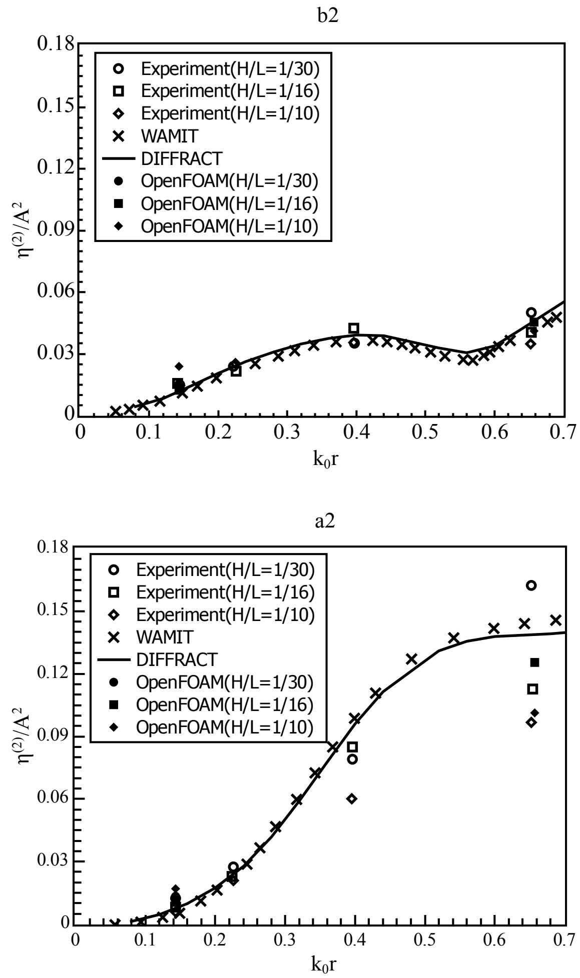


Fig.4 QTFs for double frequencies (2[nd] harmonic component) at different locations

In Fig. 4, the sum-frequency QTF diagonal (double frequency) is presented. The QTF is defined as

$$\mathrm{QTF}^{(2)} = \eta^{(2)}/A^2 \qquad (1)$$

where $\eta^{(2)}$ is the amplitude of 2[nd] harmonic (second-order). It seems smaller discrepancies are found for long waves (T=15s, k_0r=0.143) and larger difference arises for short waves (T=7s, k_0r= 0.657). The viscous flow solver in OpenFOAM can also provide reasonable predictions.

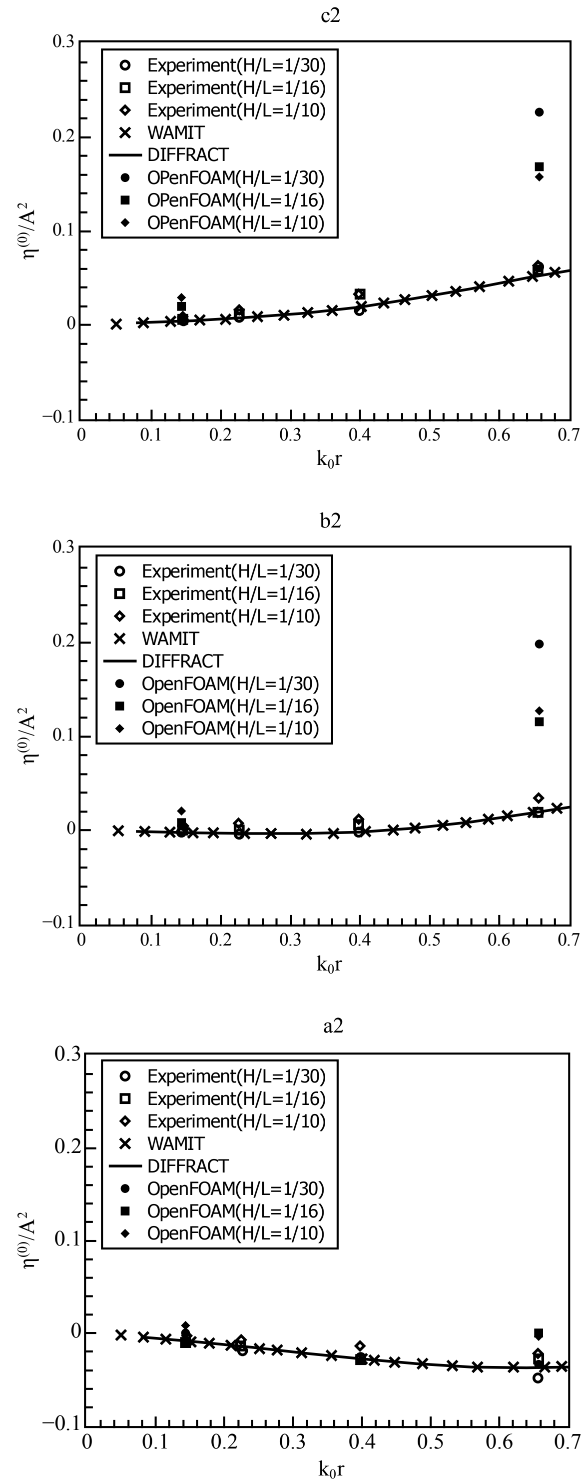


Fig.5 QTFs for zero frequencies (mean set-up/set-down) at different locations

A similar definition has been used for the difference-frequency QTF diagonal (zero frequencies), which have been plotted in Fig. 5. In the cases of regular waves, this is referred to as the mean set-up/set-down. For long waves (T=15s), both the potential flow solver and the viscous flow solver provide reasonable agreement with the experimental data. However, for waves at T=7s, the viscous flow solver over-predicts the mean set-up/set-down significantly.

CONCLUDING REMARKS

Free surface elevations around a fixed truncated cylinder subjected to monochromatic incoming waves have been investigated in the present paper. Both a potential flow solver and a viscous flow solver have been used in simulations. Numerical results have been compared with data from experiments and WAMIT simulations from Kristiansen et al. (2004).

Good agreements have been obtained between the results from potential solvers WAMIT and DIFFRACT. However, it seems these potential flow solver in the frequency domain cannot give accurate predictions for large incident waves, probably due to the limitations of the small amplitude assumption and the absence of higher order contributions above 2nd order.

Compared with potential flow solvers in the frequency domain, the viscous flow solver needs much more computational time, but more accurate predictions can be obtained in situations with large incoming waves, with the possibility of accurate results beyond the occurrence of wave breaking.

An important aspect requiring further investigation is related to viscous (drag and flow separation) effects (Stansberg and Kristiansen, 2005). For current cases in deep water, Keulegan–Carpenter numbers at the mean water level ($KC=2\pi A/D=\pi A/r$) are small (Table 2).

Table 2 KC numbers for selected wave conditions

	T=7s		T=15s	
	A	KC	A	KC
H/L=1/30	1.2740 m	0.5003	5.8500 m	2.2973
H/L=1/16	2.3888 m	0.9381	10.9688 m	4.3074
H/L=1/10	3.8220 m	1.5009	17.5500 m	6.8919

Flow separation is usually assumed to be important for KC numbers higher than 6. However, it has also been argued that it may occur at lower KC numbers (Trulsen and Teigen, 2002).

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